

# Trends in River Flow Affecting the Northeastern Reach of the San Francisco Bay Estuary over the Past 7000 Years

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**A variety of stratigraphic analyses (particle grain size, iron concentration, loss on ignition, and macrofossils) from sediments obtained from two marsh sites are used to reconstruct a middle to late Holocene record of stream flow into San Francisco Bay. Browns Island, a freshwater/brackish site, is located at the confluence of the Sacramento and San Joaquin rivers and is dominated by stands of *Scirpus americanus*. Peyton Hill is a brackish site located near Carquinez Straits and is dominated by stands of *Scirpus robustus*. Twenty-five AMS <sup>14</sup>C dates provide chronostratigraphic control. During the Holocene, discharge from the Sacramento and San Joaquin rivers was broadly comparable to modern flows; however, an extended period of higher flow began 3800 cal yr B.P. and continued for almost two millennia. At this time Browns Island supported *Phragmites communis*, a freshwater species, and Peyton Hill supported *S. americanus*. At least two floods, recognized by discrete increases in sand and silt, occurred at 3600 and 530 cal yr B.P.** © 2000 University of Washington.

## INTRODUCTION

The Sacramento and San Joaquin drainage system supplies over 50% of the freshwater used for both domestic and agricultural consumption in California (Fox *et al.*, 1990). The rivers discharge into the San Francisco Bay, across an extensive delta, and are responsible for 90% of the freshwater flow into the San Francisco Bay estuary (Conomos *et al.*, 1985; Nichols *et al.*, 1986; Peterson *et al.*, 1989). Discharge varies both annually and interannually with seasonal and longer-term climatic variability (Conomos, 1979; Cayan and Peterson, 1993; Hedgpeth, 1979). These temporal changes in discharge are the principal factors controlling salinity within the estuary (Peterson *et al.*, 1989). Changes in discharge reflect regional climate rather than local factors, because the combined drainage of the Sacramento and San Joaquin rivers encompasses over 40% of California's surface area (Nichols *et al.*, 1986;

Peterson *et al.*, 1989; Cayan and Peterson, 1993). Historical records of freshwater inflow span ca. 100 years (Peterson *et al.*, 1989). During this time extensive modification of the river system occurred (e.g., California State Water Project). Today summer inflow is routinely augmented (Nichols *et al.*, 1986); thus, our understanding of the variability of natural flows into the estuary is limited.

Recent paleoenvironmental reconstructions by Ingram and colleagues (Ingram and Sloan, 1992; Ingram and DePaolo, 1993; and Ingram *et al.*, 1996a,b) used strontium and oxygen-isotope data to determine paleosalinity and infer paleodischarge. Maximum temporal coverage of these studies ranges from 5900 to 2000 yr. Both methods highlight general trends in freshwater flow to the estuary, and a cycle of high and low discharge events of ca. 200 yr is suggested. However, there appears to be poor correlation between some events and conflicting interpretation within and between sites. For instance, Sr data indicate a low-flow regime between 90–110 and 270 cal yr B.P. (Ingram and DePaolo, 1993), yet oxygen isotopes indicate a high-flow regime between 90–150 and 220–275 cal yr B.P. (Ingram *et al.*, 1996a). Sr data also suggests a high-flow event between 2650 and 2550 cal yr B.P. (Ingram and DePaolo, 1993) and oxygen and carbon isotopes suggest a low-flow event between 2700 and 2600 cal yr B.P. (Ingram *et al.*, 1996b). The isotope analyses were run on mollusks obtained from bay cores, which may be subject to a greater degree of bioturbation and river flow disturbance than marsh cores. For instance, a core from San Pablo Bay has a hiatus of almost 1000 years (ca. 750–1670 cal yr B.P.) (Ingram *et al.*, 1996a). Bay cores are useful in tracking long-term hydrologic trends but are unlikely to record infrequent extreme events.

Additionally, Ingram and Southon (1996) have identified significant problems in the consistency of radiocarbon ages based on estuarine mollusks in San Francisco Bay. Radiocarbon analyses from five *Mytilus edulus* samples collected between AD 1939 and 1943 yielded radiocarbon ages that varied

from  $710 \pm 60$  to  $1000 \pm 70$  yr, a spread of ages of almost 300 years from an effectively coeval suite of sample. A similar analysis of the radiocarbon ages of three different species (*Mytilus*, *Macoma*, and *Ostrea*) sampled from the same stratigraphic layers in a sediment core yielded ages that spread over 1400  $^{14}\text{C}$  years. With this large an inherent reproducibility error in age estimation, the absolute timing of climatic events that are believed to be  $<300$  yr long must be considered tentative.

General circulation models (GCMs) indicate that atmospheric circulation was different from the present during much of the Holocene, as a consequence of orbitally controlled increases in summer insolation (Kutzbach *et al.*, 1993). Seasonal contrasts in insolation approached their maximum values about 9000 yr B.P. (Kutzbach and Webb, 1993) and this resulted in the enhancement of the summer low pressure system in the continental United States and the intensification of the Pacific subtropical high pressure cell (Thompson *et al.*, 1993). This atmospheric organization would have tended to steer storms northward, resulting in dry conditions in California during the early Holocene. The results of this model simulation are confirmed by paleoclimatic data from northern California (e.g., Edlund and Byrne, 1991; Koehler and Anderson, 1994; Rypins *et al.*, 1989). Insolation values gradually began to approach present values about 6000 yr B.P. Climate simulations for ca. 6000 yr B.P. indicate that the winter storm track was slightly north of its current position and that precipitation differed little from today. Paleoclimatological inferences suggest that precipitation levels in the Sierra Nevada for this period were similar or slightly drier than those at present (e.g., Edlund and Byrne, 1991; Koehler and Anderson, 1994).

The purpose of the present research is to extend the temporal database of discharge trends of the Sacramento/San Joaquin system and integrate these into an understanding of statewide changes in climate. To this end, we employ a multiproxy technique combining chemical, biological, and sedimentary records from wetland peats located near the historical boundary between brackish and freshwater marshes.

## ENVIRONMENTAL SETTING

A well-defined salinity gradient exists in the San Francisco Bay estuary (Conomos *et al.*, 1985). This salinity gradient is a function of the mixing of saline water from the Pacific Ocean and freshwater from the Sacramento and San Joaquin rivers. The Carquinez Straits marks the approximate position of the mixing zone of river water with ocean water (Krone, 1979). Surface water salinities range between 0 and 18‰, depending on the season (Conomos *et al.*, 1985). Near the confluence of the Sacramento and San Joaquin rivers salinity typically varies seasonally between about 0 and 5‰ (Conomos, 1979). During drought years saline waters can intrude up the rivers, and vegetation can change in response to the increased salt concentrations within the water and soils (Atwater *et al.*, 1979; Knight, 1980).

The marsh vegetation growing within Suisun Bay reflects the dominantly brackish conditions; vegetation changes occur gradually toward the western edge of the delta as waters progressively freshen (Atwater *et al.*, 1979; Knight, 1980). The vegetation assemblages found in brackish and fresh marshes are statistically distinct (Goman, 1998). Distinct differences also occur within marshes as a function of tidal inundation. Traditionally these marsh zones have been categorized as low, middle, and high marsh (Atwater and Hedel, 1976); however, statistical analysis of vegetation distribution within marshes in the San Francisco Bay suggests two divisions, separated by mean higher high water (MHHW) (Goman, 1998).

Both brackish and fresh marshes support a mixture of *Scirpus acutus*, *Scirpus californicus*, and *Typha angustifolia* below MHHW. Above MHHW brackish marshes near the Carquinez Straits are dominated by stands of *Scirpus robustus*, whereas toward the Delta this marsh region is dominated by *S. americanus*. Both marsh types above MHHW also support patches of *Distichlis spicata* and *Salicornia virginica* (Goman, 1996).

## METHODS

Two coring sites were selected based upon their position relative to the mixing zone (Peyton Hill) and to the confluence of the Sacramento and San Joaquin rivers (Browns Island) (Fig. 1). Each site was cored at or above MHHW. Sediment cores were collected using a Livingstone corer fitted with a plastic sleeve. At Peyton Hill marsh, two cores (PH93A and PH93B) were collected approximately 900 m inland of the bay edge in an area dominated by *S. virginica* and *D. spicata*. Dense stands of *S. robustus* grow bayward of the core site. Two sediment cores (BI92 and BI93) were also collected from Browns Island (Fig. 1). BI92 was collected from a region of marsh dominated by *S. americanus*, and BI93 was collected toward the center of the island in an area supporting *S. americanus* and *D. spicata*.

The cores from both sites were analyzed in the laboratory for particle grain size, iron concentration, percentage weight loss on ignition (LOI), and seed content. Comparisons with surveys of the same parameters from the modern marshes aided interpretations (Table 1; Goman, 1996). Sediment compaction during coring was experienced at all sites. Because the length of the sampled sediment core was consistently shorter than the measured penetration distance due to compaction, we used a simple linear extrapolation to "decompact" the core data for presentation. Depths mentioned in the text have been adjusted for compaction. All sediment cores were archived by X-radiography. Lithology and contact relationships were described using the techniques of Nelson (1992). Samples were taken at 10- to 20-cm intervals, or closer if lithostratigraphy varied at a finer resolution. BI93 was sampled every centimeter between 230 and 375 cm and thereafter every 10 to 50 cm for iron concentrations. Detailed procedures and protocols are

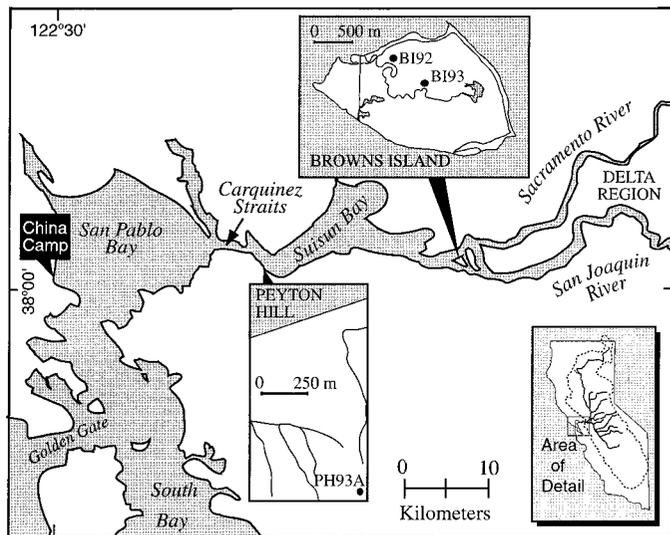


FIG. 1. Map of San Francisco Bay showing core locations and sites mentioned in text. Inset maps show state of California and drainage area of the Sacramento and San Joaquin rivers and details of individual core sites.

found in Goman (1996). Unless otherwise stated, sample size was approximately 1 cm<sup>3</sup>.

#### LOI and Iron Concentration

Organic content of the sediment was determined according to standard LOI procedures (Dean, 1974). Pizzuto and Rogers (1992) and Goman (1996) have shown that the organic content in modern marshes varies significantly according to marsh subenvironment (ANOVA, significance  $\leq 0.5$ ). Organic content increases as tidal inundation decreases and organic content increases toward the Delta (Table 1; Fig. 1).

The acid-digestible component of sediments was analyzed by a Perkin-Elmer Model 3100 atomic absorption spectrometer fitted with an HGA-600 graphite furnace, following digestion in HNO<sub>3</sub> and HCl. Thomas and Varekamp (1991) have shown that the relative amount of iron in marsh sediments can be used as an analog for tidal flooding frequency. The lower marsh regions, which are more frequently inundated by tidal water, have a higher iron concentration than the less-frequently flooded higher marsh regions. This relationship has been used successfully in several regions as a proxy for marsh subenvironment (Thomas and Varekamp, 1991; Fletcher *et al.*, 1993; Daoust *et al.*, 1996). Goman (1996) determined average surface iron concentrations from three marsh sites in the estuary (Table 1). Iron concentrations are highest at China Camp, a tidal marsh site that supports stands of *Spartina foliosa* below MHHW and *S. virginica* above MHHW. The lowest concentrations are found at Browns Island above MHHW, while concentrations from Peyton Hill and Browns Island <MHHW are indistinguishable. Surface samples have a consistently higher iron concentration than samples from depth (Goman, 1996). This may reflect recent anthropogenic contamination, as

Pb is also high in the surface sediments (Goman, 1996). Since the absolute value of iron cannot be calibrated to surface conditions due to the modern contamination, the changes in iron concentrations at depth are interpreted relative to other iron concentrations below the surface. Surface iron concentrations and organic content are strongly negatively correlated ( $P < 0.01$ ) (Goman, 1996); thus, lower LOI values should have higher iron concentrations (Fletcher *et al.*, 1993; Goman, 1996).

#### Grain Size

Samples for sediment grain size analysis were initially sieved to remove large pieces of organic matter ( $>63 \mu\text{m}$ ); the procedure then followed Folk (1980). A small sample size (1 cm<sup>3</sup>) was used, both because of the high organic content and to maintain temporal resolution. We therefore determined a simple clay:silt:sand ratio for the inorganic fraction.

Analysis of samples collected from the modern marsh plain show little grain-size variability, both between and within marshes, and clays strongly dominate the mineral component of these sediments (Goman, 1996; Pestrong, 1972). Pestrong (1972) documented a slight variation in grain size, with silts

TABLE 1  
Selected Surface Sediment Characteristics and Vegetation<sup>a</sup>

Sediment surface characteristic	<MHHW	$\geq$ MHHW
China Camp		
No. of samples	5	8
Vegetation	<i>Spartina foliosa</i>	<i>Salicornia</i>
Dominant seeds	No seeds	<i>Salicornia</i>
Organic (%)	10.3 $\pm$ 0.7	16.3 $\pm$ 3.3
Clay (%)	63.9 $\pm$ 6.0	63.0 $\pm$ 6.9
Iron (g kg <sup>-1</sup> )	55 $\pm$ 8.5	43.0 $\pm$ 8.9
Peyton Hill		
No. of samples	6	15
Vegetation	<i>S. acutus</i> , <i>S. californicus</i> , <i>T. angustifolia</i>	<i>S. robustus</i>
Dominant seeds	<i>Scirpus</i> spp., <i>Atriplex</i> , Asteraceae	<i>Salicornia</i>
Organic (%)	14.0 $\pm$ 3.0	21.5 $\pm$ 6.8
Clay (%)	58.1 $\pm$ 9.7	63.0 $\pm$ 6.9
Iron (g kg <sup>-1</sup> )	34.7 $\pm$ 5.9	35.9 $\pm$ 5.9
Browns Island		
No. of samples	4	8
Vegetation	<i>S. acutus</i> , <i>S. californicus</i> , <i>T. angustifolia</i>	<i>S. americanus</i>
Dominant seeds	<i>Scirpus</i> spp., Asteraceae	<i>Scirpus</i> spp., <i>Triglochin</i>
Organic (%)	19.4 $\pm$ 10.5	55.9 $\pm$ 13.3
Clay (%)	51.3 $\pm$ 23.2	68.4 $\pm$ 14.0
Iron (g kg <sup>-1</sup> )	37.4 $\pm$ 18.3	20.3 $\pm$ 13.8

<sup>a</sup> For further details, see Goman (1996).

dominating at the mudflat/tidal plain transition on salt marshes of southern San Francisco Bay. Changes in sediment grain size are therefore interpreted as reflecting changes in sediment deposition either caused by marsh evolution (Pethick, 1981) or as a result of floods.

### Macrofossils

Seeds and roots from 9 cm<sup>3</sup> of sediment were isolated and identified using herbarium specimens, and samples collected in the field (Hickman, 1993; Martin and Barkley, 1961; Mason, 1957; Montgomery, 1977; and Munz, 1973). Whole seeds and fragments of seeds were counted and summed for each sample layer (Goman, 1996).

Seed and root macrofossils are used to infer marsh subenvironment (Goman, 1996, 1998). A comparison of seeds found in surface sediments with the standing vegetation indicates a significant relationship ( $P \leq 0.01$ ) (Goman, 1998) and, thus, seeds are assumed to be autochthonous to the marsh, as are roots found in growth position.

### Radiocarbon Analysis

Twenty-five AMS <sup>14</sup>C dates provide chronostratigraphic control. Seeds are the preferred medium, as earlier work (Wells, 1995) showed more consistent ages and fewer age reversals using seed-derived ages than those obtained from bulk peat or root samples (Table 2). All radiocarbon dates have been calibrated using CALIB 3.0 (Table 2; Stuiver and Reimer, 1993).

## RESULTS

### Peyton Hill

Peyton Hill core A (PH93A) is 715-cm-long and the basal sediments date to 5460 cal yr B.P. (Fig. 2). The second core PH93B is only 310 cm long and no geochronologic control was obtained. The lithostratigraphy from PH93B correlates well with that of the upper portions of core A; therefore, unless specified, the following description is of core A.

From 0 to 375 cm the sediments are very-dark-brown muddy peats (LOI,  $33 \pm 13\%$ ; Fe,  $20 \pm 9$  g kg<sup>-1</sup>) with occasional thin clay laminae. A bed of sandy clay is present between 15 and 42 cm depth. Seeds of *Salicornia* and *Triglochin* are most common in the upper 311 cm. Gray clayey mud deposits (LOI  $19 \pm 7\%$ ; Fe  $26 \pm 9$  g kg<sup>-1</sup>) persist below the muddy peat deposits to the base of the core. Rare to common, very-fine to fine rootlets run through these deposits. Achenes of *Scirpus* and seeds of unidentified Cyperaceae dominate. Within the gray clayey muds, four stratigraphic reversals occur. Each reversal includes the following lithostratigraphy: bay mud is abruptly to gradually replaced by a very thin to thinly bedded silty-sand to silty-clay deposit (thickness, 4–16 cm) with abundant allochthonous debris (charcoal fragments, high seed diversity, including seeds of *Potamogeton*) that in turn is abruptly overlain

by a discrete layer of organic-rich sediment that contains discrete clay laminae (2–5 mm thick). The clayey peats are present at 481–503, 531–542, 552–565, and 586–612 cm depth. *Potamogeton* seeds are present throughout the core, except between 291 and 405 cm. The distribution of clay is fairly constant ( $67 \pm 14\%$ ), although a region of anomalously high silt was found from 416 to 446 cm (75% by weight of inorganic fraction). Sedimentation rates at Peyton Hill vary from 0.11 to 0.14 cm yr<sup>-1</sup>, except for two periods of much higher sedimentation (0.31 and 0.21 cm yr<sup>-1</sup>) (Table 3).

### Browns Island

BI92 core is 779 cm long and has a basal age of 6310 cal yr B.P. BI93 core is 1061 cm long and has a basal date of 6710 cal yr B.P. The top 1 m of BI93 was not recovered. Peat comprises the upper 8 m of both cores (Figs. 3 and 4). This peat is composed of roots, rhizomes, and stems in variable states of preservation, with a clear increase in humification with depth (Fig. 3) LOIs for BI92 and BI93 were  $55 \pm 17$  and  $65 \pm 7\%$ , respectively *Scirpus* achenes (*S. californicus*, *S. americanus/ acutus*, and *S. robustus*) dominate the peat sections of the cores, with the exception of the portions between 350–512 cm at BI92 and 427–705 cm at BI93, where leaf sheafs of *Phragmites/Typha* dominate. Clay is the predominant inorganic component of the peats (BI92,  $72 \pm 17\%$ ; BI93,  $92 \pm 3\%$ ), which have no inorganic laminations, except for a silty-sandy lamina at 73 cm in core BI92. The silty sand horizon is approximately 5 mm thick and contains abundant mica, foraminifera (*Trochominna inflata*), and *Potamogeton* seeds. Iron concentrations in the peats are higher in BI92 ( $17 \pm 10$  g kg<sup>-1</sup>) than for BI93 ( $8 \pm 4$  g kg<sup>-1</sup>), indicative of more-frequent tidal inundation at this site.

In BI93, a large woody rhizome (6-cm thick) rested abruptly on a clay layer at 809 cm depth. Overlying this rhizome was a 23-cm-thick layer of peat with a crumbly soil structure and relatively low cohesion compared to other peat in the core. Beneath the large rhizome, the sediments between 809 and 942 cm are predominantly clay with common organic laminations (LOI  $34 \pm 25\%$ ). Below 942 cm, a marked shift to silty sand occurs (LOI,  $4 \pm 0.5\%$ ; silt,  $73 \pm 5\%$ ; sand,  $5 \pm 5\%$ ). Elevated concentrations of iron ( $29 \pm 8$  g kg<sup>-1</sup>) and a high seed diversity are found in the inorganic sediments from BI93. *Najas* and *Zannichellia* seeds, both submerged fresh- and brackish-water plants, are common in the silty sands.

The mean rate of sedimentation at the two Browns Island coring sites is 0.16 cm yr<sup>-1</sup> at BI92 and 0.17 cm yr<sup>-1</sup> at BI93 (Table 3). However, considerable variability in rates of sedimentation occurs within the cores. Peak sedimentation rates are measured in core BI92 between 526 and 553 cm (0.41 cm yr<sup>-1</sup>) and 180 and 277 cm (0.31 cm yr<sup>-1</sup>). The lowest sedimentation rates were measured near the basal peats of BI92 (0.05 cm yr<sup>-1</sup>). In the BI93 core sedimentation rates are highest in the basal silty sands and clays where a value of 0.24 cm yr<sup>-1</sup> is calculated (Table 3).

**TABLE 2**  
**Radiocarbon Data for Samples from Peyton Hill and Browns Island**

Depth (cm) <sup>a</sup>	Sample <sup>b</sup>	CAMS Laboratory No. <sup>c</sup>	Age ( <sup>14</sup> C yr B.P.)	Calibrated age range <sup>d</sup>
Peyton Hill				
<b>309 (310)</b>	<i>Salicornia</i> and <i>Scirpus</i> seeds	<b>20552</b>	<b>2580 ± 60</b>	<b>2715–2756 (2736)</b>
<b>353 (358)</b>	<i>Scirpus</i> seeds	<b>20553</b>	<b>2920 ± 60</b>	<b>2954–3201 (3078)</b>
<b>406 (407)</b>	<i>Scirpus</i> seeds	<b>20554</b>	<b>3270 ± 60</b>	<b>3400–3563 (3482)</b>
<b>450 (455)</b>	<i>Scirpus</i> seeds	<b>20555</b>	<b>3410 ± 60</b>	<b>3575–3699 (3637)</b>
<b>590 (592)</b>	<i>Scirpus</i> seeds	<b>20556</b>	<b>4220 ± 60</b>	<b>4646–4840 (4743)</b>
<b>642 (656)</b>	<i>Scirpus</i> seeds	<b>20557</b>	<b>4420 ± 60</b>	<b>4871–5211 (5041)</b>
<b>705 (708)</b>	<i>Scirpus</i> seeds	<b>20558</b>	<b>4740 ± 60</b>	<b>5328–5582 (5455)</b>
Browns Island 1992				
<b>6 (40)</b>	<i>Scirpus</i> seeds	<b>4795</b>	<b>Modern</b>	<b>0 (0)</b>
<b>12 (80)</b>	<i>Scirpus</i> seeds	<b>4794</b>	<b>430 ± 60</b>	<b>339–517 (428)</b>
12 (80)	Stem	4793	Modern	0 (0)
43 (66)	Root	4792	Modern	0 (0)
<b>43 (66)</b>	<i>Scirpus</i> seeds	<b>4791</b>	<b>480 ± 60</b>	<b>496–540 (518)</b>
112 (116)	Root	4790	Modern	0 (0)
<b>160 (180)</b>	<i>Scirpus</i> seeds	<b>4789</b>	<b>1430 ± 60</b>	<b>1287–1351 (1319)</b>
160 (180)	Root	4788	Modern	0 (0)
203 (204)	Leaf	4787	<b>1210 ± 60</b>	1059–1223 (1141)
<b>272 (277)</b>	<b>Leaf</b>	<b>4786</b>	<b>1740 ± 60</b>	<b>1552–1711 (1632)</b>
339 (350)	Leaf	4785	2060 ± 60	1937–2107 (2022)
<b>339 (350)</b>	<i>Scirpus</i> seeds	<b>4784</b>	<b>2470 ± 100</b>	<b>2351–2741 (2546)</b>
<b>523 (526)</b>	<i>Scirpus</i> seeds	<b>9962</b>	<b>3580 ± 210</b>	<b>3624–4147 (3886)</b>
528 (532)	Root	4782	2730 ± 60	2763–2867 (2815)
<b>547 (553)</b>	<b>Leaf</b>	<b>4781</b>	<b>3630 ± 60</b>	<b>3840–4063 (3952)</b>
<b>605 (606)</b>	<b>Leaf</b>	<b>4780</b>	<b>4092 ± 60</b>	<b>4092–4343 (4218)</b>
634 (636)	Leaf	4779	4470 ± 70	4880–5286 (5083)
648 (651)	Leaf	4778	<b>5410 ± 260</b>	5915–6447 (6181)
<b>687 (692)</b>	<i>Scirpus</i> seeds	<b>9961</b>	<b>4290 ± 60</b>	<b>4829–4870 (4850)</b>
715 (719)	Leaf	4775	<b>5150 ± 80</b>	5762–5983 (5873)
723 (728)	Leaf	4774	<b>4930 ± 70</b>	5597–5733 (5665)
<b>747 (756)</b>	<i>Scirpus</i> seeds	<b>4773</b>	<b>4930 ± 60</b>	<b>5599–5728 (5664)</b>
<b>758 (769)</b>	<b>Bulk peat</b>	<b>4771</b>	<b>5190 ± 60</b>	<b>5907–5988 (5948)</b>
<b>779 (794)</b>	<b>Leaf</b>	<b>4772</b>	<b>5530 ± 100</b>	<b>6212–6412 (6312)</b>
Browns Island 1993				
<b>409 (409)</b>	<i>Scirpus</i> seeds	<b>10110</b>	<b>2920 ± 60</b>	<b>2952–3201 (3077)</b>
<b>801 (801)</b>	<b>Woody debris</b>	<b>12190</b>	<b>4970 ± 60</b>	<b>5645–5841 (5743)</b>
801 (801)	Woody debris	12185	4640 ± 50	5302–5450 (5376)
<b>928 (929)</b>	<i>Scirpus</i> seeds	<b>12187</b>	<b>5390 ± 60</b>	<b>6103–6281 (6192)</b>
<b>928 (929)</b>	<b>Bulk peat</b>	<b>12189</b>	<b>5340 ± 40</b>	<b>6035–6187 (6111)</b>
1000 (1000) <sup>e</sup>	Woody debris	12183	5030 ± 70	5666–5896 (5781)
<b>1060 (1064)</b>	<b>Leaves</b>	<b>12184</b>	<b>5880 ± 90</b>	<b>6574–6845 (6710)</b>

Note. Samples in bold are used for age estimates.

<sup>a</sup> Depths in parentheses are decompacted sediment depths used to calculate rates of sedimentation (Goman, 1996).

<sup>b</sup> Roots, stems, and leaves are from herbaceous marsh plants.

<sup>c</sup> Lawrence Livermore National Laboratories, Center for Accelerator Mass Spectrometry.

<sup>d</sup> Calibrated using CALIB 3.0 (Stuiver and Reimer, 1993) and 1 $\sigma$  error range as reported by CAMS. Numbers in parentheses are the midpoints of calibrated range.

<sup>e</sup> Sample identified as contamination (Goman, 1996).

### Interpretation

We interpret the stratigraphy in these deposits to record the past 6700 years of marsh evolution and fluvial discharge into Suisun Bay. Events prior to 5500 cal yr B.P. are interpreted from data retrieved from the Browns Island cores. Events since then are documented in the stratigraphy of both marshes.

Zonations provided below are based on a compilation of all proxy data at the two sites.

#### Zone 5 (6700–6200 cal yr B.P.)

The early Holocene Sacramento and San Joaquin rivers controlled sediment deposition at Browns Island until about

Peyton Hill 1993 (PH93)

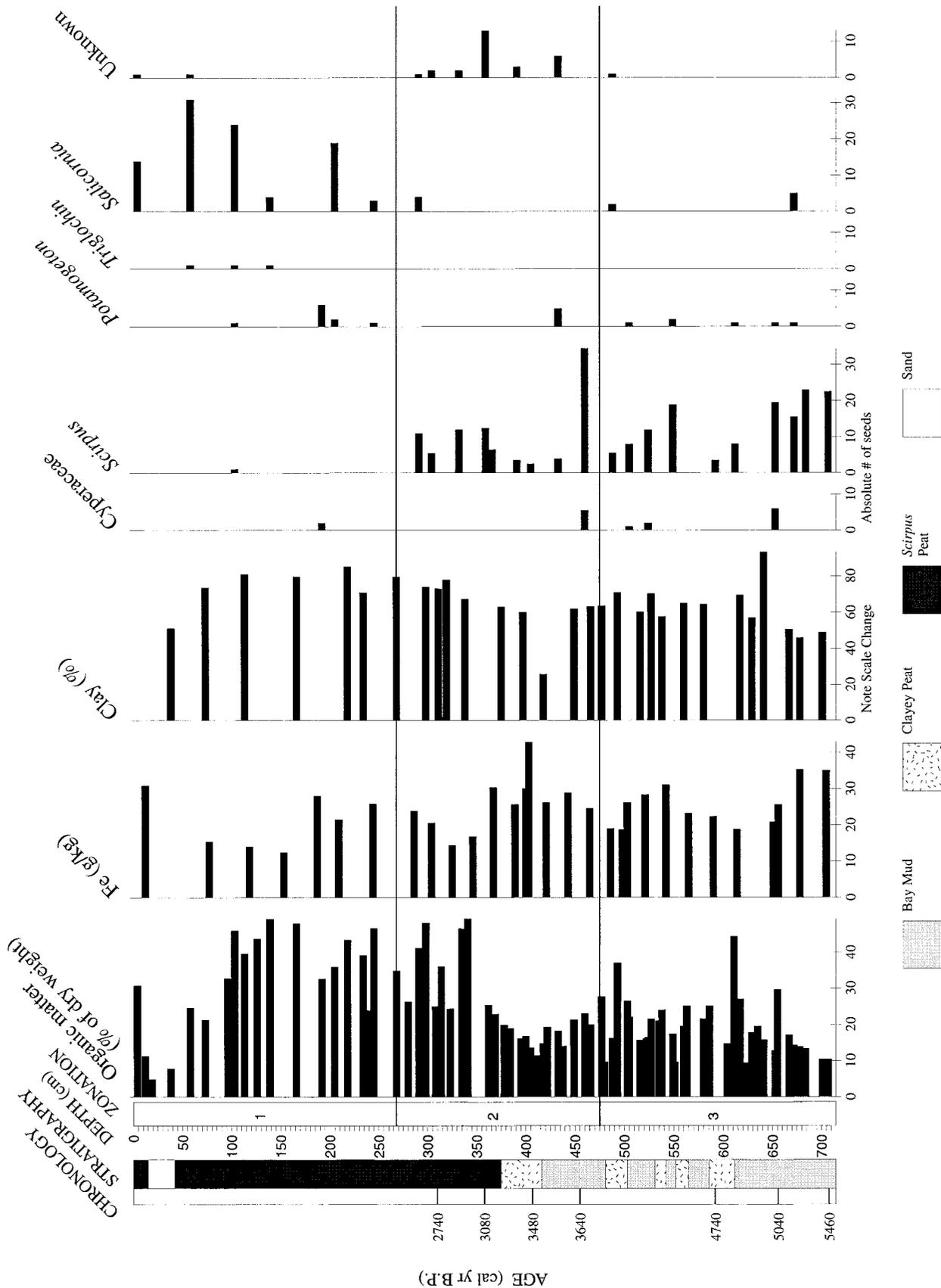


FIG. 2. Summary diagram presenting sedimentary, geochemical, and macrofossil stratigraphy for the 1993 Peyton Hill core (PH93A).

**TABLE 3**  
**Calculated Rates of Sedimentation**

Sediment accumulation rate depth range (cm) <sup>a</sup>	Dominant sediment matrix	Sediment accumulation rate (cm yr <sup>-1</sup> )	Approximate corresponding zone <sup>b</sup>
<b>Peyton Hill</b>			
0–309 (0–310) <sup>c</sup>	Muddy peats	0.11	1
309–353 (310–358)	Muddy peats	0.14	2
353–406 (358–407)	Muds	0.12	3
406–450 (407–455)	Muds	0.31	
450–590 (455–592)	Mixed	0.12	
590–642 (592–656)	Muds	0.21	
642–705 (656–708)	Muds	0.13	
<b>Browns Island 1992</b>			
0–43 (0–66) <sup>d</sup>	Peat	0.13	1
43–160 (66–180)	Peat	0.14	
160–272 (180–277)	Peat	0.31	
272–339 (277–350)	Peat	0.08	2
339–523 (350–526)	Peat	0.13	
523–547 (526–553)	Peat	0.41	3
547–605 (553–606)	Peat	0.2	
605–687 (606–692)	Peat	0.14	
687–747 (692–756)	Peat	0.08	
747–758 (756–769)	Peat	0.05	4
758–779 (769–794)	Peat	0.07	
<b>Browns Island 1993</b>			
0–409 (0–409) <sup>c</sup>	Peat	0.13	2
409–801 (409–801)	Peat	0.15	3
801–928 (801–929) <sup>e</sup>	Clays with organic laminations	0.16	4
928–1060 (929–1064)	Silty sands	0.24	5

<sup>a</sup> Decompressed depths and the midpoint of the calibrated age range are used to calculate rates of sedimentation (Table 2).

<sup>b</sup> For zonation see text. Zone boundaries are determined by stratigraphy; therefore, radiocarbon dates used to calculate sedimentation may straddle a zone boundary.

<sup>c</sup> No date was obtained from the top sediments. This rate assumes that at 0 cm age is modern.

<sup>d</sup> Two sediment cores were obtained for the top section of BI92. Because of overlap between the cores, dates obtained from the longer of the two cores are used.

<sup>e</sup> The dates at 928 cm have been averaged, and the oldest date from 801 cm was used.

6200 cal yr B.P. The relatively coarse nature of these sediments and the presence of seeds of the freshwater plants *Najas* and *Zannichellia*, which do not grow at the site today, indicate freshwater fluvial conditions (Fig. 4). Sea level had not yet inundated this region of the San Francisco Bay Estuary (Atwater *et al.*, 1977).

#### Zone 4 (6200–5500 cal yr B.P.)

At Browns Island, incipient brackish tidal marshes formed and drowned frequently during this zone. We attribute this to a nonuniform rate of relative sea-level rise, first inundating Browns Island and depositing subtidal mud deposits. Then, as sedimentation outpaced sea-level rise, tidal marshes formed and were subsequently drowned by a more-rapid rate of sea-level rise. This sequence repeated itself at least 18 times (Fig. 4). The greater influence of saline water is indicated by the replacement of seeds of freshwater plants by achenes of *Scirpus*, probably *S. californicus* or *S. acutus*. The long-term trend is toward shoaling and less-frequent inundation, indicated by

the gradual decline in iron concentration and the gradual increase in LOI at BI93. The large woody fragment found in the BI93 core at 809 cm (~5700 cal yr B.P.) appears to have been deposited on the island following a large flood, and not by coseismic subsidence as was previously hypothesized (Goman, 1996).

#### Zone 3 (5500–3800 cal yr B.P.)

During this period at Browns Island, the decline in inundation frequency continued, as indicated by the low iron concentrations, higher organic content, and *S. americanus* achenes. This stratigraphic change reflects the maturation of the marsh plain toward MHHW elevations. At Peyton Hill, the zone 3 lithostratigraphy, high iron content, and low organic content suggest lower intertidal conditions (Fig. 2). We interpret the four stratigraphic reversals within this zone at Peyton Hill as reflecting periods of higher-than-average river flow from the Sacramento/San Joaquin river system. The deposition of the allocthonous debris and coarser material resulted in the aggra-

Browns Island 1992 (BI92)

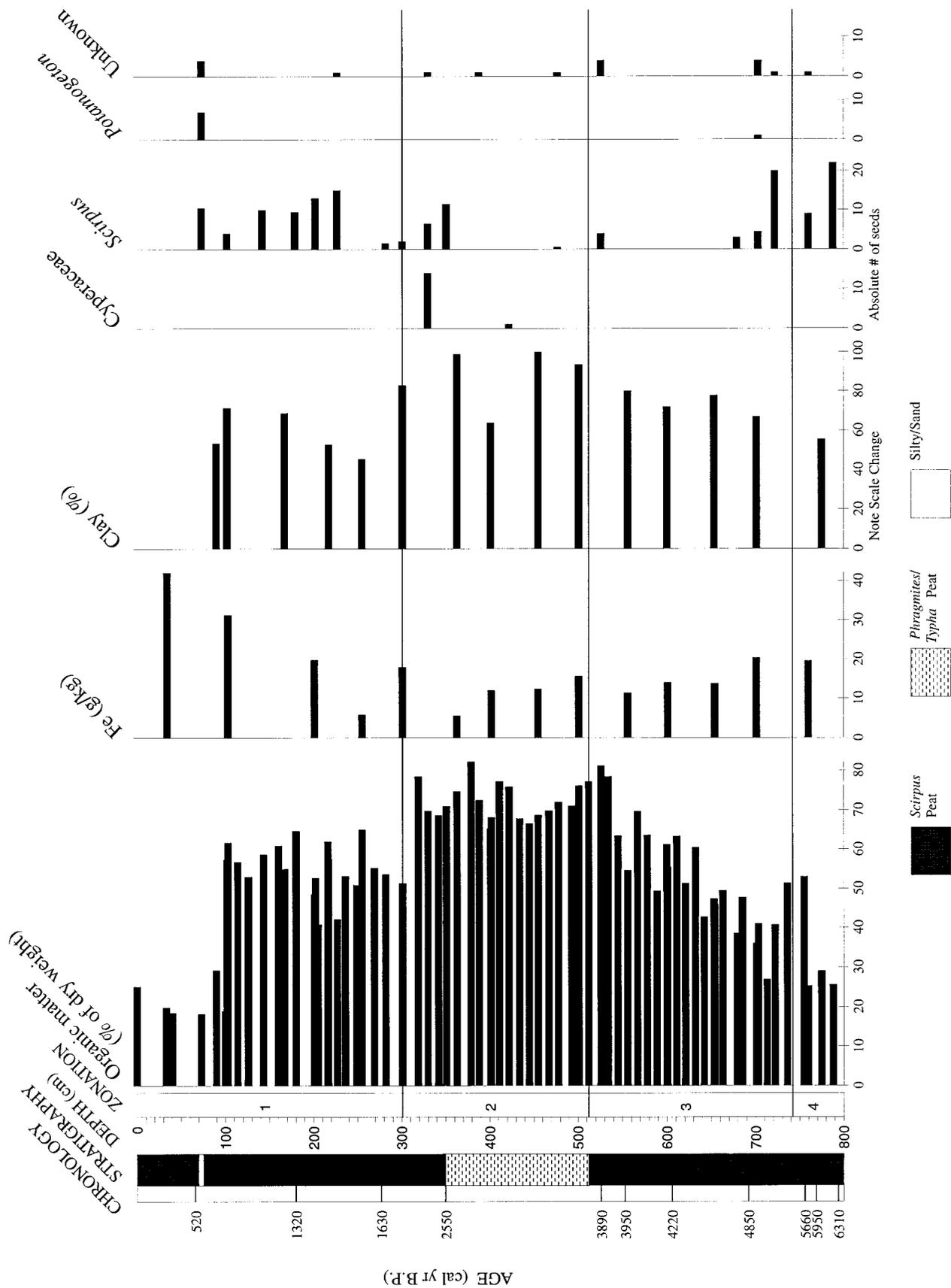
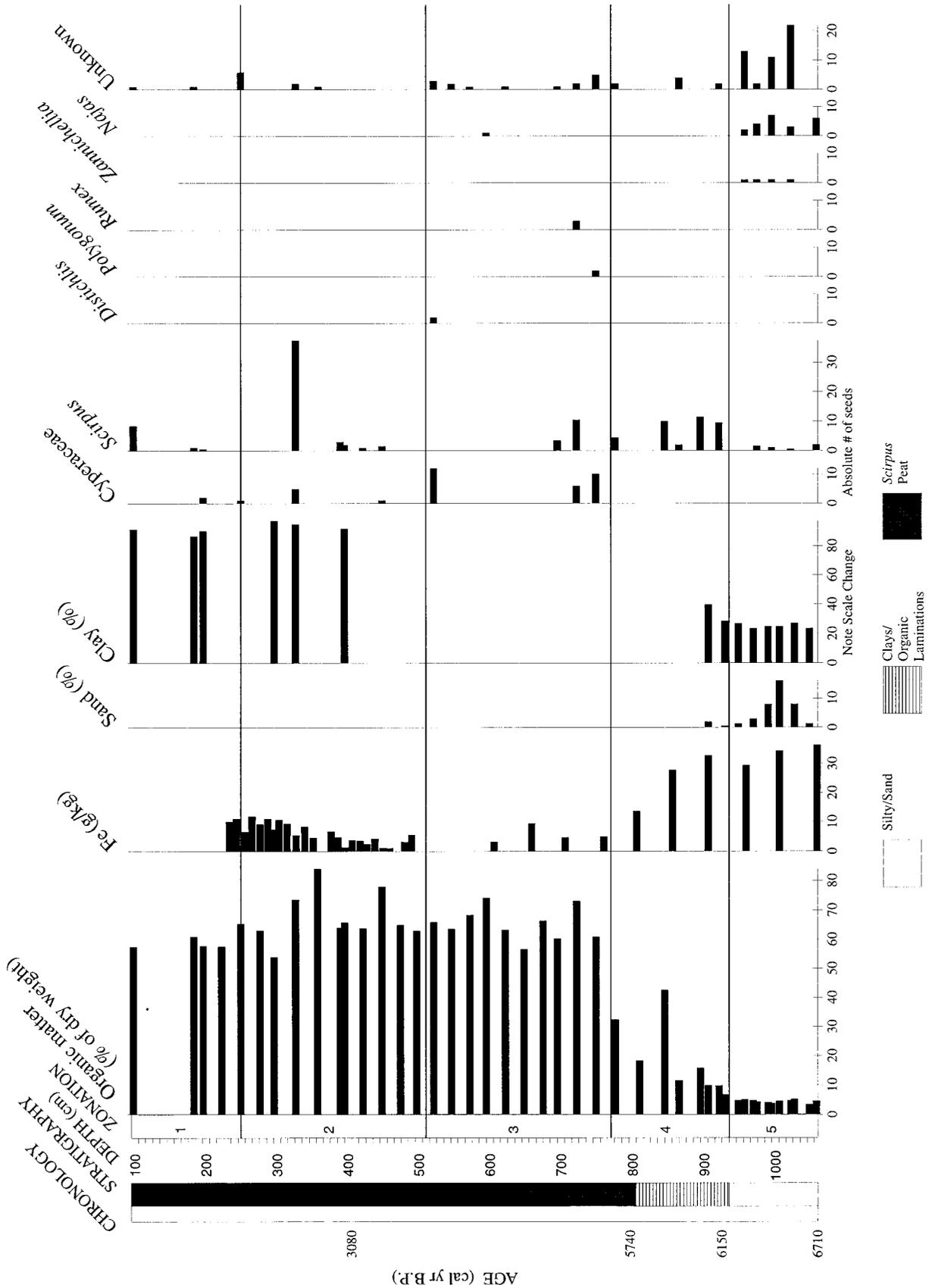


FIG. 3. Summary diagram presenting sedimentary, geochemical, and macrofossil stratigraphy for the Browns Island 1992 core (BI92).

Browns Island 1993 (BI93)



**FIG. 4.** Summary diagram presenting sedimentary, geochemical, and macrofossil stratigraphy for the Browns Island 1993 core (BI92). Top meter was not retrieved. Sediments were analyzed for iron every centimeter between 250 and 375 cm. The results for this section are presented as a running 10-cm average. Samples were not processed for grain size between 4 and 9 m.

dation of the marsh plain to an upper intertidal elevation. Relative sea-level rise eventually submerged the marsh, again resulting in the return to deposition of bay mud in the lower intertidal zone. During the same time period, episodic high river flow is indicated at Browns Island by the deposition of the freshwater aquatic seeds of *Najas* and *Potamogeton* (Goman, 1996). The subsequent submergence of the Peyton Hill marsh below midtide levels may be accounted for either by tectonically driven marsh subsidence, a maintained rise in eustatic sea level, or declining water levels from the river system. We prefer a combination of the latter two explanations as these account for the cessation of allocthonous debris deposition and the submergence of the marsh by rising sea level, producing the gradual return to subtidal deposition. Similar stratigraphic reversals occurred in the basal sediments of BI93. The occurrence of this stratigraphic signature in the basal sediment of both cores indicates that during the period of incipient marsh emergence the marsh and its stratigraphy are extremely sensitive to small changes in water depth and inundation frequency.

#### Zone 2 (3800–2000 cal yr B.P.)

Peat at both sites has high organic content and low iron content during this time, reflecting a continued decline in inundation and maturation of the marsh toward MHHW levels. At Browns Island macrofossils differ from the previous zone, as remains of *Phragmites communis* were identified. Atwater (1980) also found *Phragmites* at comparable depths from a series of undated cores from Browns Island. *Phragmites* is common upstream in the fresher water of the Sacramento Delta today. At Peyton Hill, achenes of *S. americanus* were identified in this zone. An oceanward shift in species indicates that salinity in the region of the Carquinez Straits was comparable to the modern summer salinity at Browns Island, a decrease from ca. 8–18 to 0–2‰ (Conomos *et al.*, 1985). We conclude, therefore, that between 3800 and 2000 cal yr B.P. salinity was lower than today and that summer freshwater discharge was considerably greater than it is today.

Evidence for a large discharge event is also found within zone 2, at about 3600 cal yr B.P. At Peyton Hill, the grain size abruptly coarsens to silt, the iron content increases, and higher rates of sedimentation occurred (407–455 cm; Fig. 3 and Table 3). The few seeds present in this section are probably allocthonously derived, given their battered condition and the absence of *in situ* roots. At Browns Island, more subtle changes in the stratigraphy were observed at this horizon. There is an increase in inorganic sedimentation, a decrease in total root material, an increase in root size, and the dominance of near-vertical growing roots. At China Camp, west of the Carquinez Straits, a silt lamina is present at a horizon of comparable age, suggesting that this flood event impacted the entire estuary (Goman, 1996).

#### Zone 1 (2000–0 cal yr B.P.)

This zone is characterized by a return to more-saline conditions, reflected in the shift in plant species. At Peyton Hill, *S. americanus* was succeeded by *Salicornia* and *Triglochin*, while at Browns Island *S. americanus* again dominates the biostratigraphy. Marsh elevation at the core locality was maintained at MHHW. Browns Island was affected by at least one extreme flood event ~530 cal yr B.P., when silty sand, foraminifera, and seeds of *Potamogeton* were deposited on the island (73 cm; Fig. 3). No comparable silty mica-rich horizon has been identified at Peyton Hill for this time period. The thick sand bed at Peyton Hill is thought to represent recent construction of a road through the site, as comparable sand beds are not present in a transect of short surface cores (M. Goman, unpublished data). However, thin clay-rich laminae are found within the peats at Peyton Hill, as are seeds of *Potamogeton*, suggesting occasional seasonal flooding.

### DISCUSSION AND CONCLUSIONS

Our data from zones 4 and 3 (6200 to 3800 cal yr B.P.) indicate that bay salinity was probably comparable to present values. This result compares well with other paleoclimatic data (Edlund and Byrne, 1991; Koehler and Anderson, 1994) and further adds confirmation to the GCM simulations for this time period (Thompson *et al.*, 1993).

However, our data deviate from the GCM-modeled trends between 3800 and 2000 cal yr B.P. The evidence for the decline in estuarine salinity during zone 2 suggests increased precipitation in the Sacramento/San Joaquin watershed. These findings are consistent with evidence of Neoglacial fluctuations of climate in the western United States (Burke and Birkeland, 1983; Currey, 1990). In the San Francisco Bay, and more broadly across California, a variety of paleoclimate studies also indicate increased precipitation during this time period. A rise of Mono Lake to a high stand began approximately 3800 cal yr B.P. (Stine, 1990), and in the Mojave Desert, a shallow lake existed at ca. 3900 cal yr B.P. (Enzel *et al.*, 1989). At Nichols Meadow, in the Sierra Nevada, evidence indicates rising groundwater and saturation of the meadow ca. 3000 yr B.P. (Koehler and Anderson, 1994). At San Pablo and Richardson Bays prior to 2000 cal yr B.P. average salinity was lower than today (Ingram and DePaolo, 1993). Enzel *et al.* (1989) hypothesize that a weakened subtropical high in the eastern North Pacific enabled anomalously low pressure to form along the west coast of the United States, thereby permitting the penetration of cyclonic winter storms much farther south than is normal today.

Unlike evidence from other studies in the region (Hughes and Brown, 1992; Graumlich, 1993; Stine, 1994; and Ingram *et al.*, 1996a,b), the stratigraphy presented here provides no evidence of drought. Decreased inundation frequency as a result of maturation toward MHHW results in marshes that are not

effective recorders of droughts. They are, however, sensitive to extreme floods. A large flood occurred about 3600 cal yr B.P., evidence of which is found throughout the estuary, as well as upstream from Browns Island. West (1977) attributed the rapid deposition of a silty clay deposit, approximately 140 cm thick and deposited sometime between 4400 and 3100 cal yr B.P., to a period of higher river flow. A second flood deposit, dating to ca. 530 cal yr B.P. at Browns Island, correlates with a flood deposit identified in the Sacramento Valley (Sullivan, 1982), and may correlate with an unconformity present in a core from San Pablo Bay and attributed by Ingram *et al.* (1996a) to an extreme hydrological event. Farther south, Schimmelmann *et al.* (1998) identified a flood deposit in the Santa Barbara Basin dating to A.D. 1418, which they suggest may correspond to strong El Niño events (Schimmelmann *et al.*, 1998).

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